



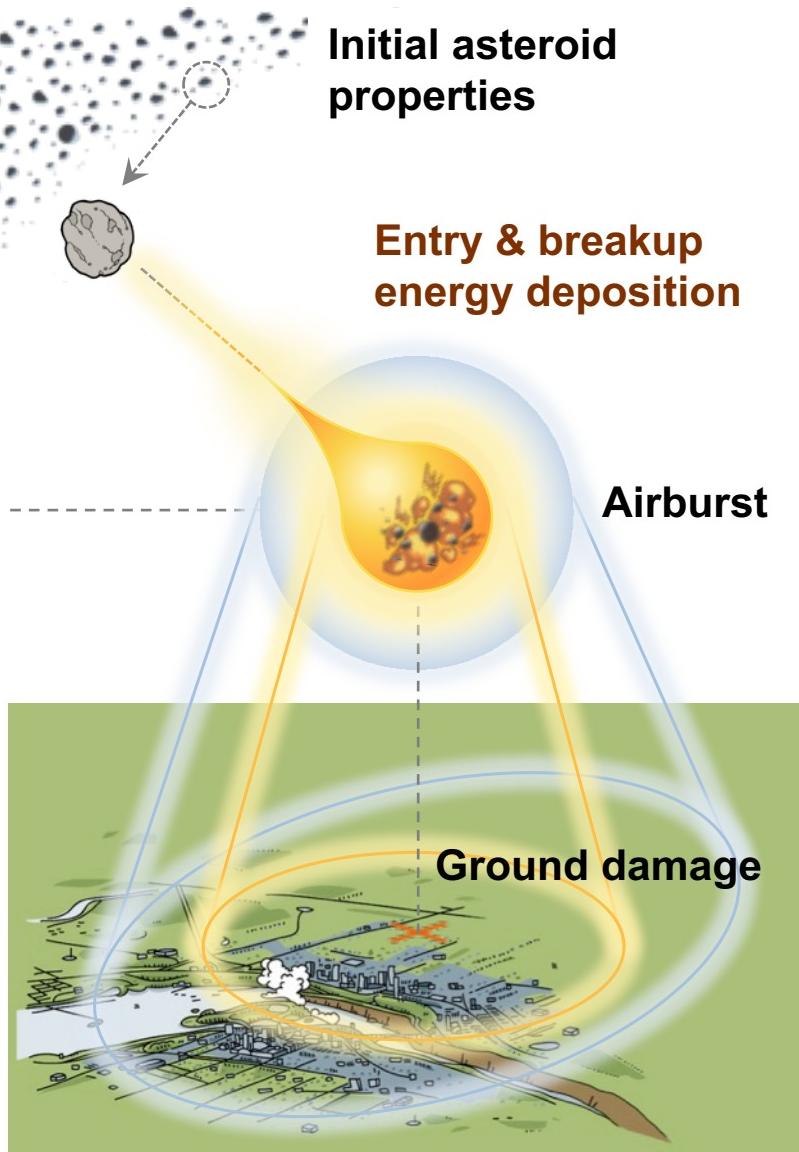
Modeling the Atmospheric Breakup of Varied Asteroid Structures: Inferences for the Chelyabinsk Meteor

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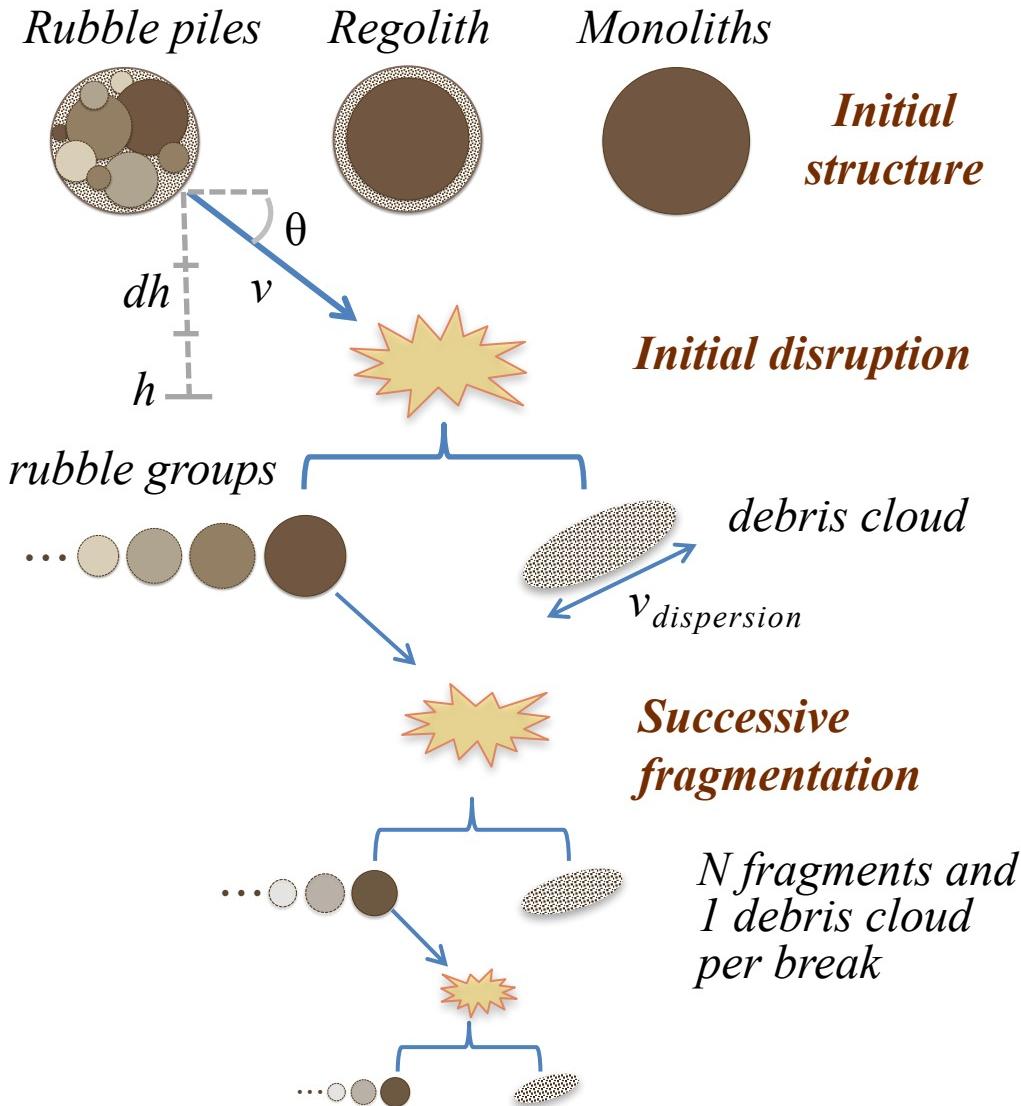
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Asteroid Impact Risk Modeling



- Fragment-Cloud Model (FCM)
 - Models energy deposited in the atmosphere during entry and breakup
 - Energy deposition used to estimate airburst altitudes and ground damage
- FCM results can also be matched to observed meteor light curves
 - Infer pre-entry asteroid properties
 - Investigate different breakup characteristics
 - Guide model refinements
 - Bound parameter ranges
- Current effort is expanding FCM to represent varied initial asteroid structures

Fragment-Cloud Model (FCM)



Flight integration:

$$dm/dt = -0.5\rho_{air}v^3A\sigma$$

$$dv/dt = \rho_{air}v^2AC_D/m - g\sin\theta$$

$$d\theta/dt = (v/(R_E+h) - g/v)\cos\theta$$

$$dh/dt = v\sin\theta$$

Fragmentation condition:

$$\rho_{air}v^2 > \text{Strength } (S)$$

Fragment strengths increase with decreased size

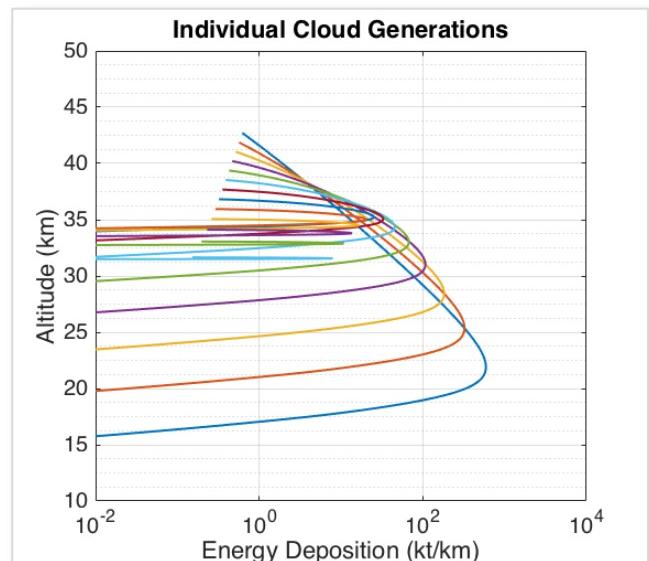
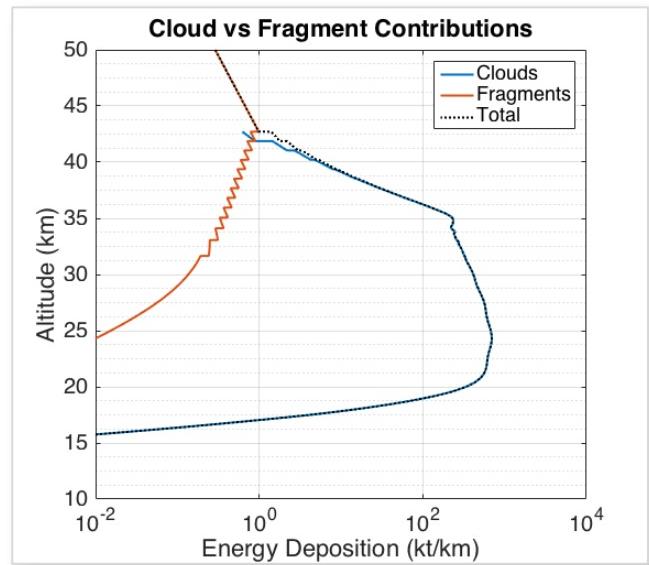
$$S_{child} = S_{parent}(m_{parent}/m_{child})^\alpha$$

Clouds broaden and slow under common bow shock

$$v_{disp.} = v_{cloud}(C_{disp}A\rho_{air}/\rho_{debris})^{1/2}$$

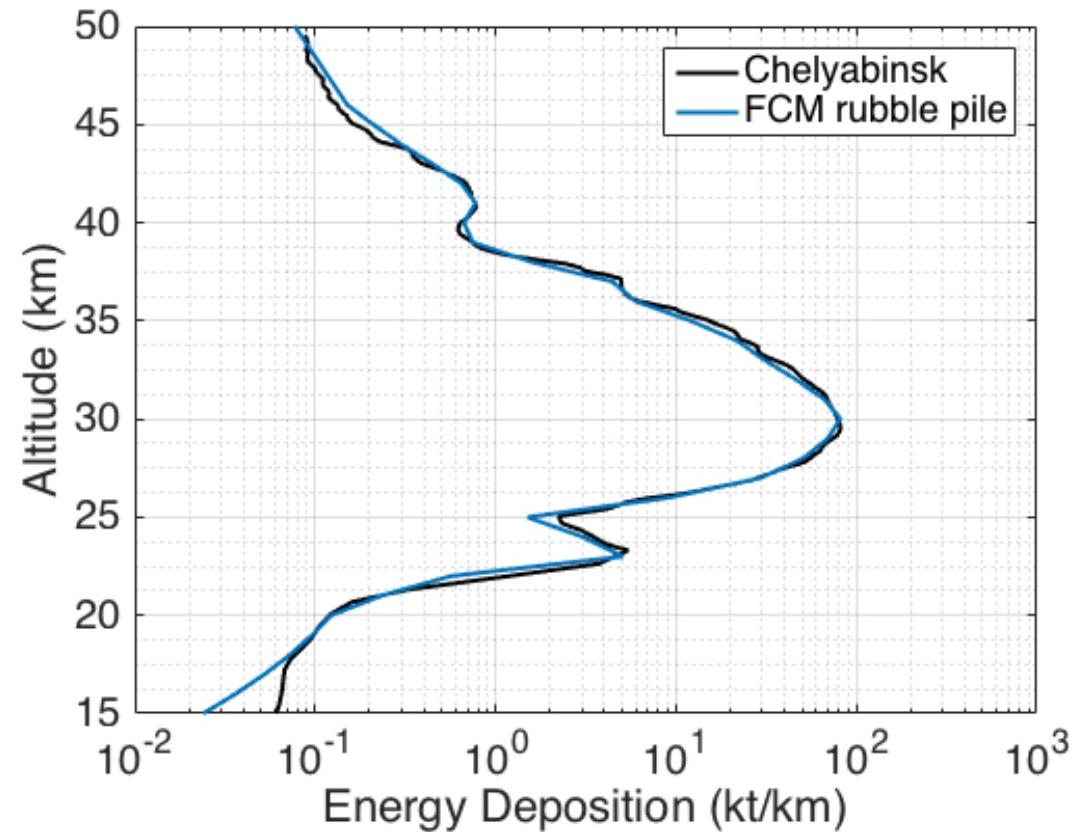
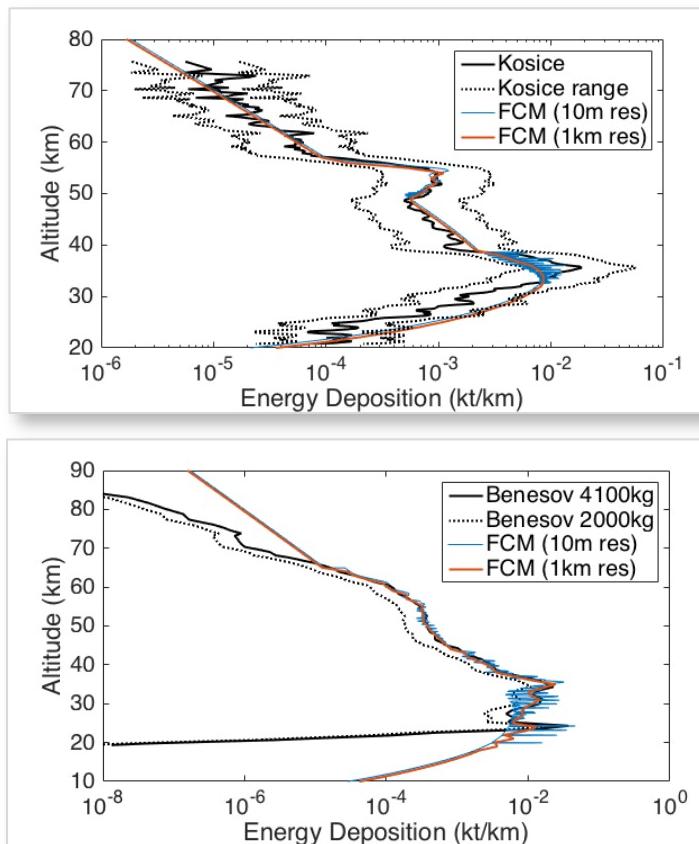
Energy Deposition ('Edep')

- Energy deposition computed as change in total kinetic energy of all fragment and cloud components as a function of altitude (kt/km)
- FCM energy deposition mechanisms:
 - Debris clouds deposit the bulk of the energy as they rapidly spread
 - Fragments serve to distribute the release of varied cloud masses
 - Large clouds released higher up produce broad, gradual flares
 - Small clouds released lower down produce sharper spikes



Observed Meteor Modeling

- FCM approach combined with variable initial structures can match a range of energy deposition profiles and features from observed meteor light curves.



Chelyabinsk Modeling Approach

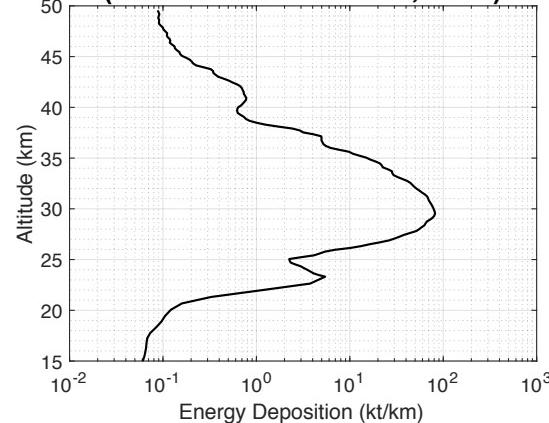
- Initial entry and mass estimates (Popova et al. 2013):
 - 19.8 m diameter
 - 19.16 km/s at 18.3°
 - 3.3 g/cm³ meteorite-based density
- Vary FCM inputs to match energy deposition profile from observed light curve (Brown et al., 2013).
- Parameters are set as initial inputs and are not tuned along the entry.
- FCM parameters varied:
 - Initial rubble fragments/debris
 - Initial aerodynamic strengths
 - Number and mass distribution of fragments per break
 - Cloud mass fraction per break
 - Strength scaling exponent (α)
 - Ablation coefficient (σ)
 - Cloud dispersion coefficient (C_{disp})

Observed Light Curve

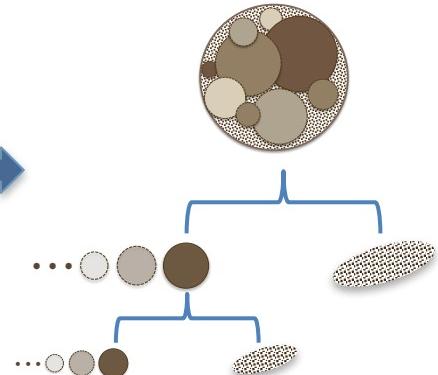


Credit: Aleksandr Ivanov, creative commons license
https://en.wikipedia.org/wiki/Chelyabinsk_meteor

**Energy Deposition from Light Curve
(data from Brown et al, 2013)**

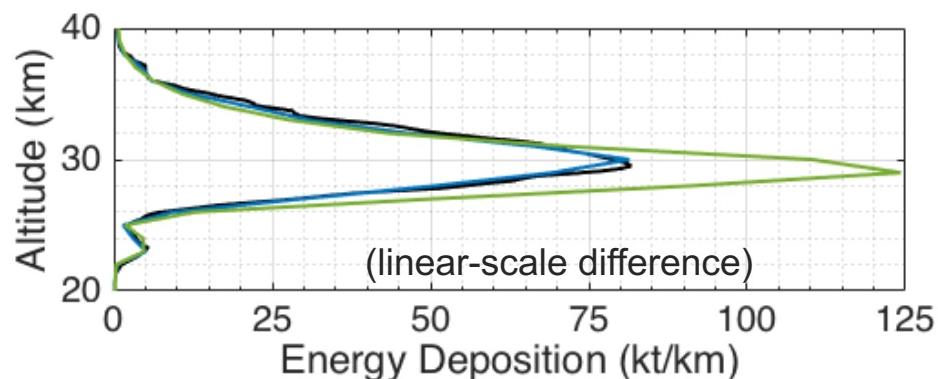
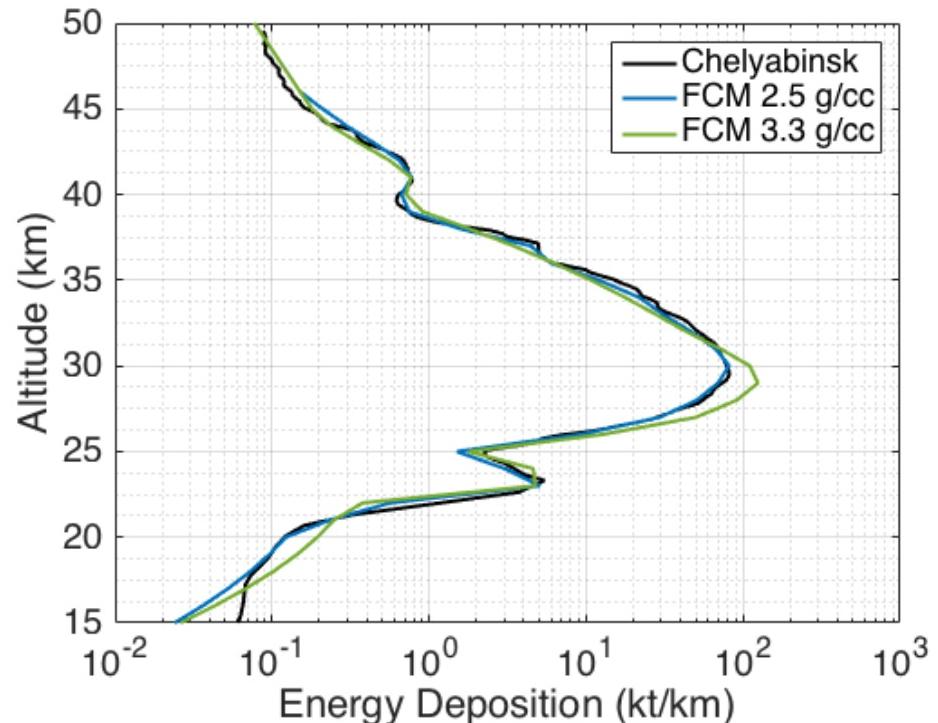


FCM Breakup Modeling

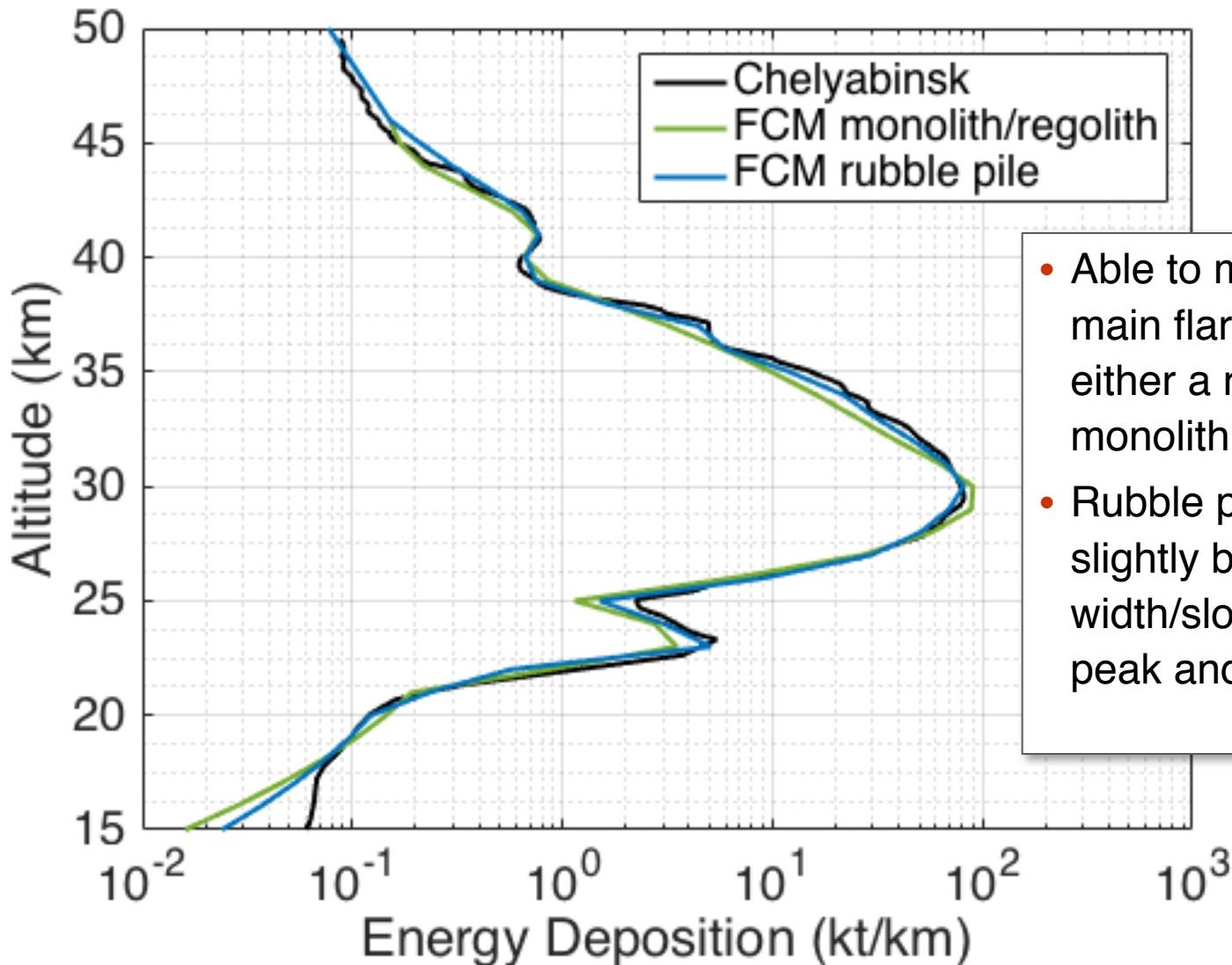


Pre-Entry Density/Mass

- Cases using meteorite-based density (3.3 g/cc) consistently exceeded peak energy deposition by ~50%
- Lower initial mass and bulk density better matched peak energy deposition
 - 9–10M kg (reduced from 13M kg)
 - Bulk density ~2.2–2.6 g/cc
 - Maintained 3.3 g/cc material density
 - Gives macroporosity ~21–33% compared to meteoritic density
 - Consistent with macroporosity ranges between fractured bodies (15–25%) or rubble piles (30–70%) (Britt et al., 2003, Asteroids III).

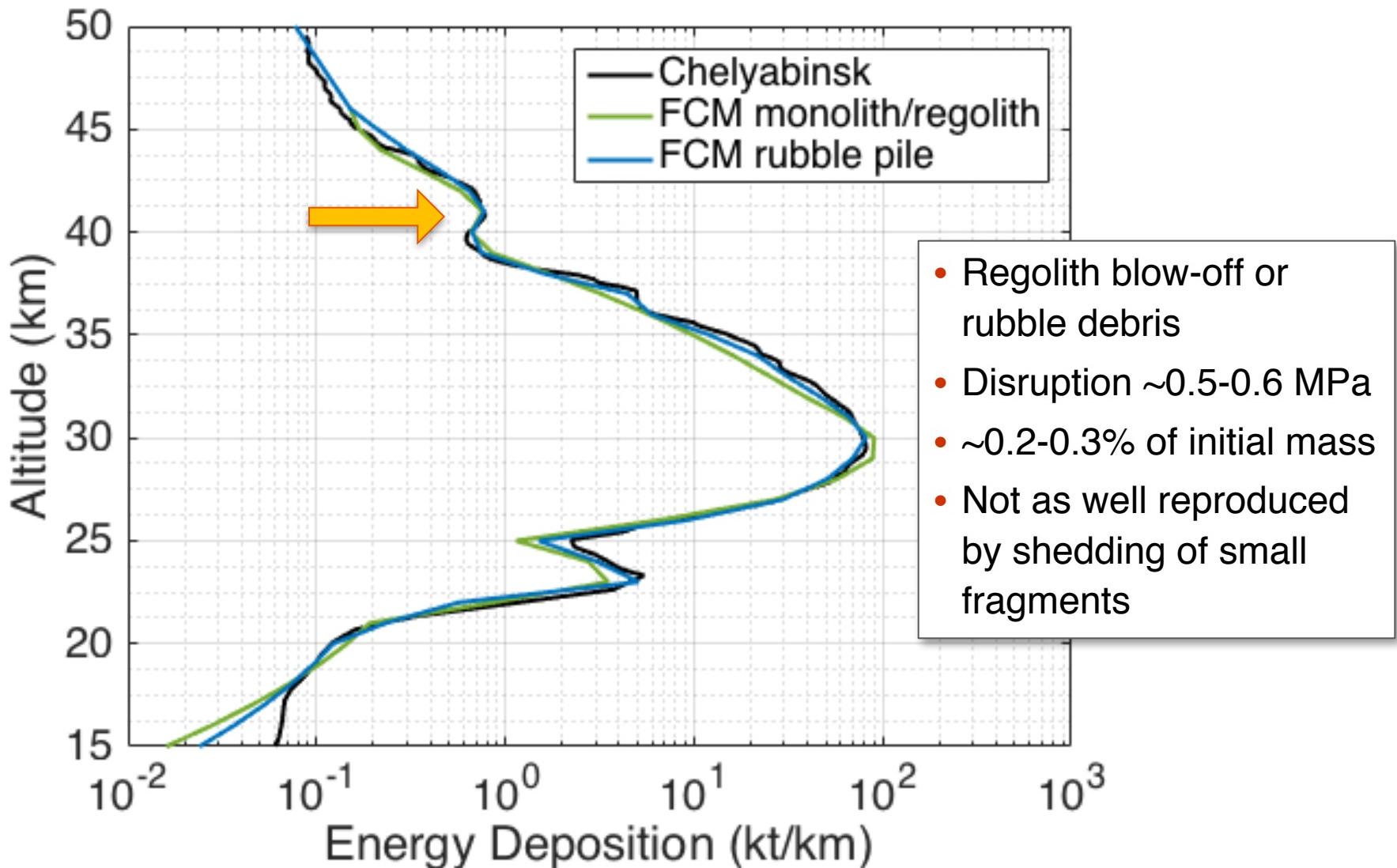


Pre-Entry Structure

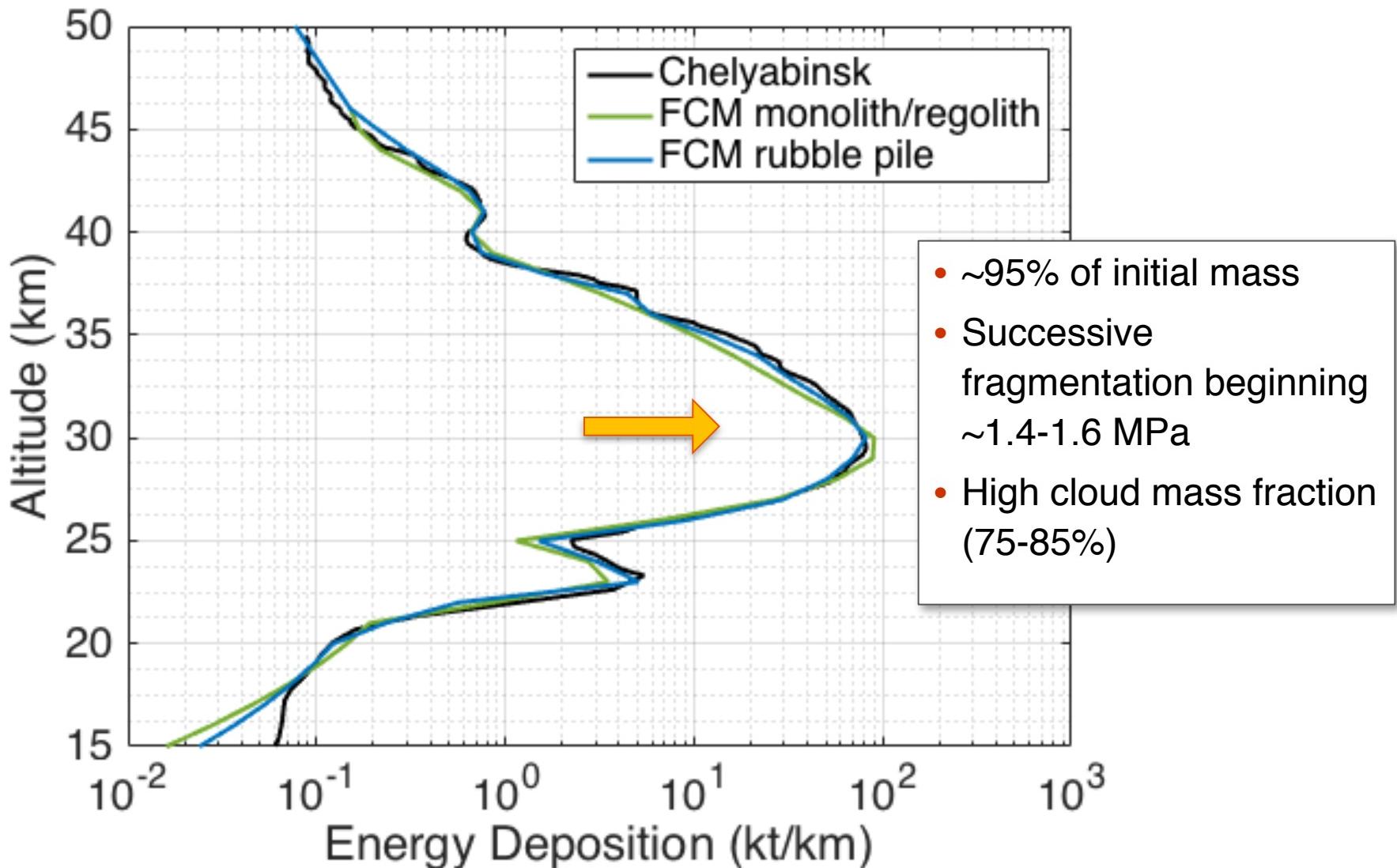


- Able to match all three main flare features using either a rubble pile, or a monolith with regolith.
- Rubble pile provides slightly better fits to the width/slope of the main peak and the lower peak

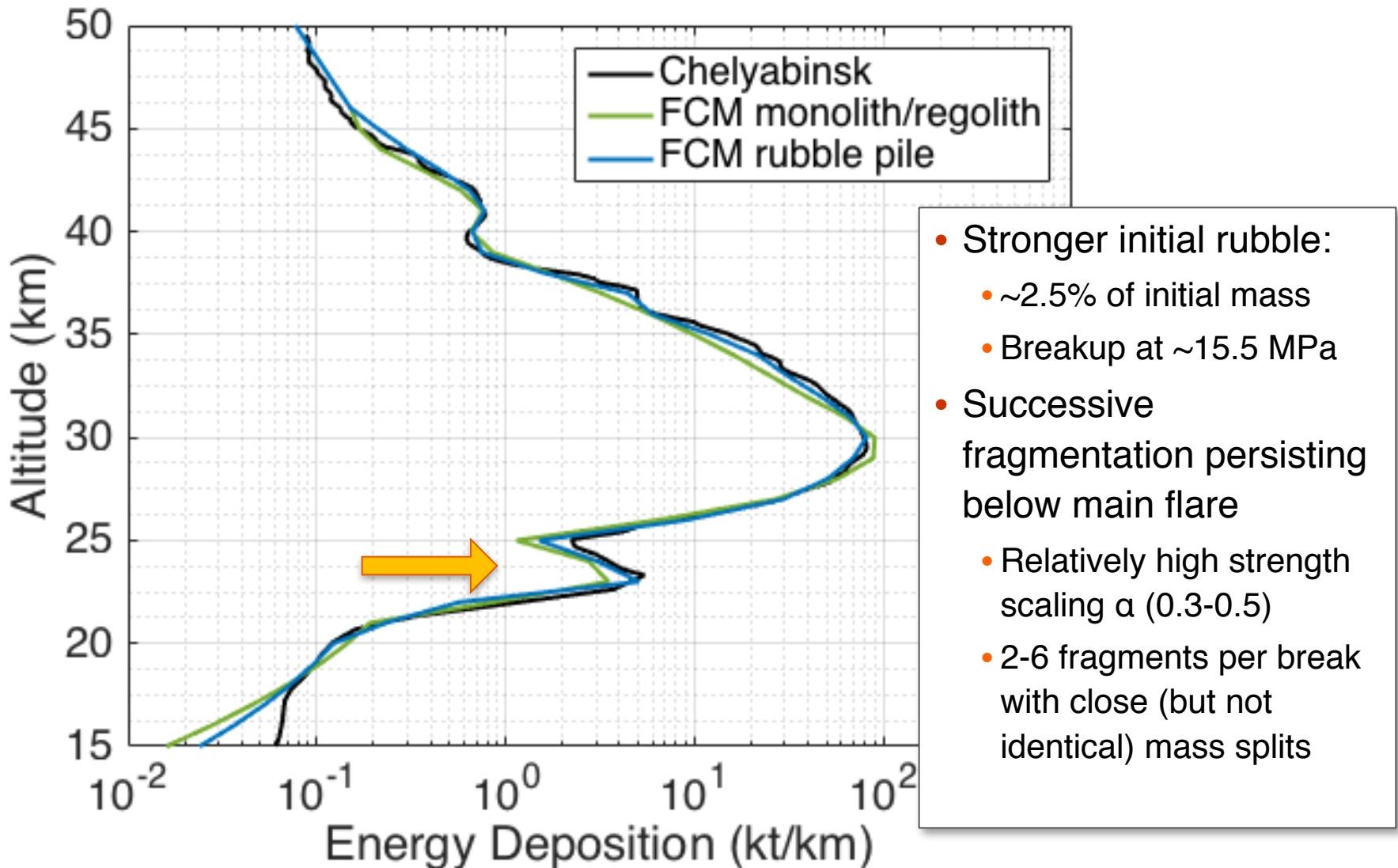
Flare Characteristics: Upper Flare



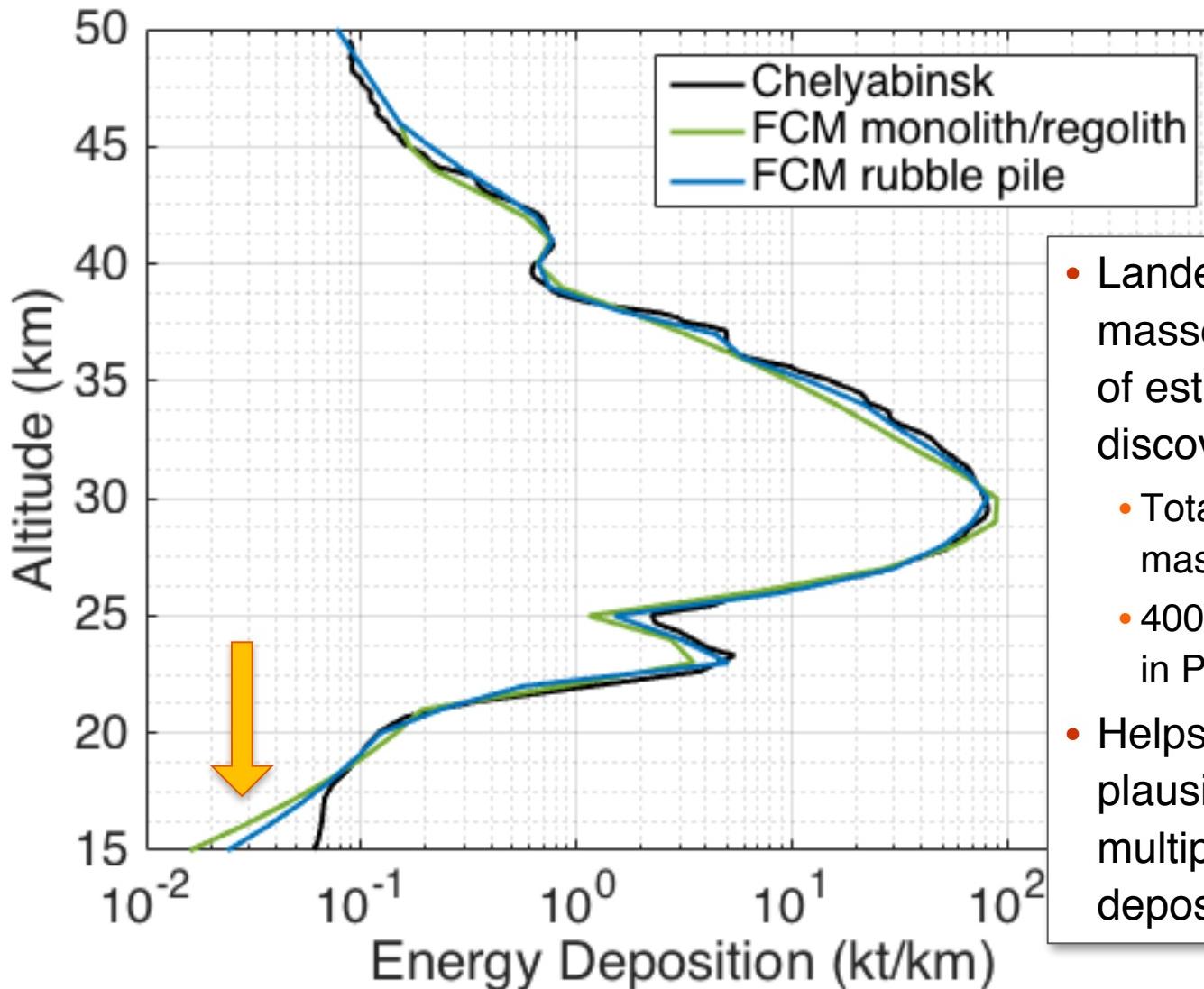
Flare Characteristics: Main Flare



Flare Characteristics: Lower Flare

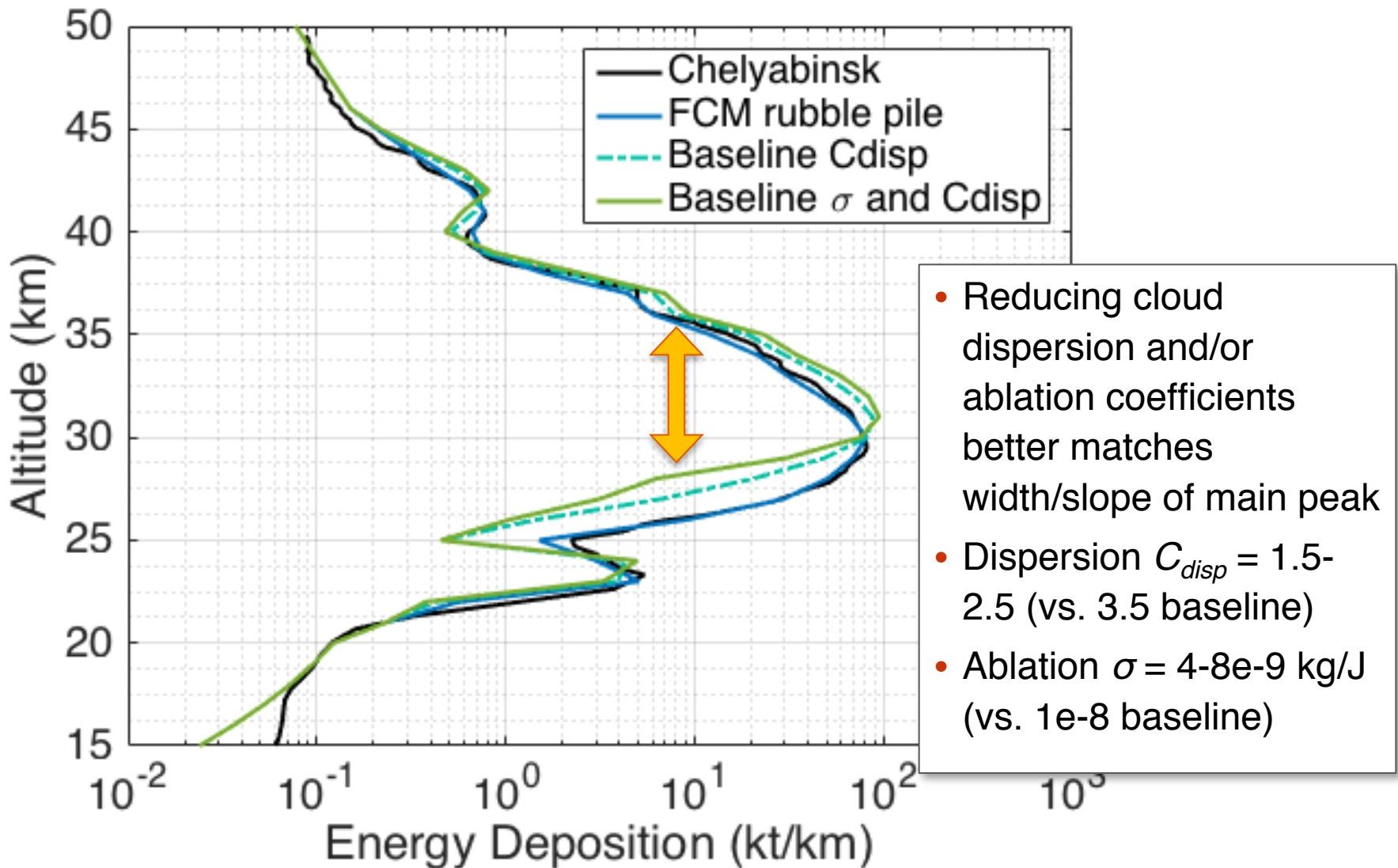


Landed Fragment Mass



- Landed fragment masses within ballpark of estimates from discovered falls
 - Total fallen fragment mass 5000–6500 kg
 - 4000–6000 kg estimated in Popova et al. 2013
- Helps constrain the most plausible cases from multiple energy deposition matches

Cloud Modeling Refinement



Summary & Future Work

- Developed FCM capability for modeling breakup and energy deposition of different asteroid structures
 - Produces realistic variety of energy deposition features, enabling very good matches to observed meteors.
 - Demonstrated how we can use those matches to make inferences about asteroid characteristics.
 - Found potential parameter refinements for modeling debris clouds.
- Risk assessment applications
 - Analytic approach efficient enough to run the large numbers of cases needed for probabilistic risk assessments, yet variable enough to represent a wide range of potential asteroid structures.
 - Provides a way move beyond the typical point-source estimates and incorporate the different energy deposition rates into ground damage estimates.
- Ongoing and future development:
 - Initialize rubble pile distributions using inverse power law distributions of sizes.
 - Refine parameters for cloud spread rates using hydrocode simulations
 - Explore effects of varied energy deposition profiles on ground damage compared to point-sources estimates (CFD simulations)
 - Automate a curve-matching optimizer to enable more comprehensive inference and thorough exploration of the parameter space
- Paper available online: **L.F. Wheeler et al., Icarus (2017)**, A fragment-cloud model for asteroid breakup and energy deposition. <https://doi.org/10.1016/j.icarus.2017.02.011>